

Direct photons at low transverse momentum – a QGP signal in pp collisions at LHC

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We investigate photon production in a scenario of quark-gluon plasma formation in proton-proton scattering at 7 TeV. It is shown that thermal photon yields increase quadratically with the charged particle multiplicity. This gives an enhanced weight to high multiplicity events, and leads to an important photon production even in minimum bias events, where the thermal photons largely dominate over the prompt ones at transverse momentum values smaller than 10 GeV/c.

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The QCD phase diagram tells us that a new kind of matter, the quark gluon plasma (QGP), can be formed at very high temperature or at very high density via high energy collisions. Such matter has probably been observed in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC). At least there seems to be no doubt that matter expands collectively, governed by a hydrodynamical expansion. This has essentially been proved based on studies of azimuthal anisotropies, where for example elliptical flow and in particular its mass dependence can hardly be explained without considering strong collectivity. It was for the first time in heavy ion physics that hydrodynamic models were able to describe such non-trivial features correctly, and it seems also clear that the corresponding liquid is almost perfect, in the sense of having very small viscosity.

Originally hydrodynamics was only thought to present a valid description for almost central collisions of heavy nuclei, where the volume is (relatively) big. But it seems that this approach works very well for all centralities. There is also no fundamental difference observed between CuCu and AuAu, although the copper system is much smaller. Systems much smaller than central AuAu also fit well into this fluid picture. Finally it is more and more accepted that the famous ridge structure observed in angle-rapidity dihadron correlation [1] is due to fluctuating initial conditions, which are subsequently transformed into collective flow [2]. Here, the relevant scale for applying hydrodynamics is not the nuclear size, but the size of the fluctuations, which is typically 1-2 fermis.

Is QGP formation a nuclear phenomenon? Or can it be formed in pp scattering, as proposed originally in refs. [3–5] and advocated more recently in [2, 6–8]? Based on the above discussion, there is no reason not to treat proton-proton scattering in the same way as heavy ions, namely incorporating a hydrodynamical evolution. This approach makes clear predictions for many variables, so the Nature will tell us whether the approach is justified or not. Therefore it will be extremely interesting to think about the implications of such a mini QGP, how such a small system can equilibrate so quickly, and so on. It would be an enormous waste of opportunities, not to consider this possibility, since a vast amount of proton-

proton data will be available very soon, concerning all kinds of observables.

What makes pp scattering at LHC energies interesting in this respect, is the fact that at this high energy multiple scattering becomes very important, where a large number of scatterings amounts to a large multiplicity. In such cases, very large energy densities occur, even bigger than the values obtained in heavy ion collisions at RHIC – but in a smaller volume. Several authors discussed already the possibility of a hydrodynamical phase in pp collisions at the LHC, to explain the ridge correlation [2, 9, 10], or to predict elliptic flow [11–14].

In heavy ion physics, one of the possible “signals” of QGP formation is photon production, since a hot plasma radiates a large amount of “thermal” photons, which dominate the spectra at small transverse momenta, whereas large momenta are dominated by photons from hard processes in nucleon-nucleon scatterings. Such a “low p_t enhancement” has been observed at RHIC, see [15, 16]. Photons are an interesting plasma signal, since they are emitted from the interior of the hot matter, and do not interact any more, contrary to hadronic observables. The only question here: are there kinematic windows (p_t range) where thermal photons can clearly be distinguished from other sources?

In this paper we will study the possibility of a QGP formation in proton-proton scattering, by making use of the properties of photons as a signature. So we will discuss direct photon production, both prompt photons and thermal photons in details, in pp collisions at 7 TeV.

But before discussing the details, we want to show in Fig. 1 the final result. We show first of all prompt photon calculations at 200 GeV and at 1.8 TeV, compared to data from RHIC and Tevatron. There seems to no need for thermal photon production at 200 GeV, whereas at Tevatron, there are no data at low p_t , and therefore no conclusion can be drawn on the question of thermal photon production. Interesting are the results we obtain for pp scattering at 7 TeV: we show in Fig. 1 the prompt photons (dashed-dotted line) and the full contribution, prompt plus thermal ones (full line). Here we get an important contribution from thermal photons, which largely dominate the spectrum up to roughly 10 GeV/c. Very

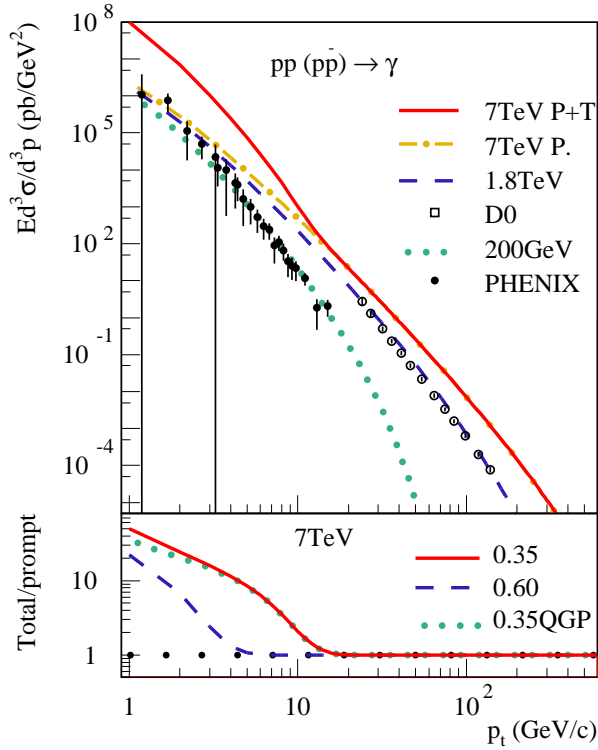


Figure 1: (Color Online) Upper panel: Prompt photons (dashed-dotted line) and the sum of prompt photons and thermal photons (full line) in pp at 7 TeV. We also show prompt photon production in pp at 200 GeV (dotted line) and in $p\bar{p}$ at 1.8 TeV (dashed line) compared to PHENIX data [17] (full cycles) and D0 data [18] (open circles). Lower panel: the ratio of the total photon production (prompt + thermal) to the prompt photons for pp collisions at 7 TeV. See text.

important here is the very early stage, where the temperatures are highest. To show this, we plot in the lower panel the ratio of the total photon production (prompt + thermal) to the prompt photons. The full line corresponds to the full line in the upper panel – the default calculation corresponding to a hydrodynamical evolution starting at $\tau_0 = 0.35$ fm/c. The dashed line is the result of a calculation starting at $\tau_0 = 0.60$ fm/c. The thermal contribution is considerably reduced, but still important. Since early production is very important, it is clear that photons from the hadronic phase are negligible. The dotted line in the lower panel corresponds to the default calculation again, but counting only photons from the QGP phase. So the main message is that we get a very important thermal contribution for transverse momentum up to 10 GeV/c, due to the very early emission from the QGP phase. But why is the contribution so big, and why do we get such a big effect only at very high energies (why not already in p+p collisions at RHIC)? To answer these questions, we have to discuss more details, as will be done in the following chapters.

The production of high- p_t prompt photons in $pp(p\bar{p})$ collisions is an important testing ground for perturbative

QCD. Primarily due to the relatively clean signal provided by photons and their point-like coupling to quarks, this enables a probe of the dynamics of the underlying hard scattering subprocesses that involve strong interactions. The cross section for the fully inclusive production of a single prompt photon schematically reads [19]

$$\begin{aligned} \frac{d\sigma^{\text{prompt}}}{dyd^2p_t} &= \sum_{ab} \int dx_a dx_b G_a(x_a, M^2) G_b(x_b, M^2) \frac{\hat{s}}{\pi} \\ &\times \delta(\hat{s} + \hat{t} + \hat{u}) \left[\frac{d\sigma}{dt}(ab \rightarrow \gamma + X) \right. \\ &\left. + K \sum_c \frac{d\sigma}{dt}(ab \rightarrow cd) \int dz_c \frac{1}{z_c^2} D_{\gamma/c}(z_c, Q^2) \right] \end{aligned}$$

where $G_a(x_a, M^2)$ is parton distribution functions (PDF) in proton, the elementary processes $ab \rightarrow \gamma + X$ are Compton scattering $qg \rightarrow \gamma q$ and annihilation $q\bar{q} \rightarrow g\gamma$ and the second term covers high order contribution with photon fragmentation functions $D_{\gamma/c}(z_c, Q^2)$ being the probability for obtaining a photon from a parton c which carries a fraction z of the parton's momentum. In our calculation, MRST2001 [20] PDF is employed and $K=2$ is used to take into account high order contribution of hard parton production. The obtained p_t spectrum of prompt photons at three energies are the curves shown earlier in Fig. 1.

In the following, we will introduce another source of photon production, completely new in the field of proton-proton scattering, which will substantially modify the spectra in the low p_t region. Therefore we have to discuss the question of how well we understand “normal” photon production in this area. There are several factors, like the theoretical scales, parton distribution functions, and so on. Extensive investigation on the effects from different renormalization scales and factorization scales and from different PDF such as GRV-94, MSRT and CETQ-2M have been done[21]. More recently PDF are discussed in the context of parton saturation: a slightly lower production in the low p_t region may expected when using corresponding PDF. Another topic to be discussed concerns higher order contributions, which get more important with increasing collision energy [22] and may enhance low p_t photon production. However, the resummation calculation of [23] shows only a few percent increase.

As discussed earlier, crucial for our discussion is the fact that at LHC energies multiple scattering in the spirit of the Gribov-Regge approach becomes important, and therefore the number ν of Pomerons is a key quantity for each event. Whereas in heavy ion collisions the centrality is used to define event classes, we classify here events according to the Pomeron number ν . In the so-called Eikonal approximation, the probability of ν Pomerons reads $\text{Prob}(\nu) \propto \chi_\nu^\nu$, where Pomerons are treated as identical, and χ depends on nothing but the collision energy \sqrt{s} . However, this approximation ignores two facts: the collision energy is shared between the ν Pomerons, and initial valence quarks of the two colliding protons destroy the simplified picture of having identical Pomerons.

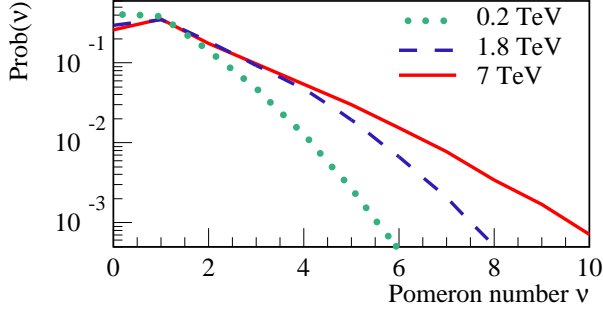


Figure 2: (Color Online) Probability distribution of Pomeron number ν at three collision energies.

A more sophisticated multiple scattering theory[24, 25] was developed to improve this approximation, and the resulting Pomeron distribution is shown in Fig.2, for pp collisions at $\sqrt{s} = 200\text{GeV}$ (dotted line), $p\bar{p}$ at 1.8 TeV (dashed line) and pp at 7 TeV (solid line).

From the multi-string configurations for a given ν , the energy-momentum tensor

$$T^{\mu\nu} = (e + P)u^\mu u^\nu - P g^{\mu\nu} \quad (1)$$

at some initial time τ_0 is obtained, where e is energy density, P is pressure, u^μ is local four fluid velocity and $g^{\mu\nu} = \text{diag}(1, -1, -1, -1)$ is the metric tensor. The subsequent evolution is governed by conservation laws of energy and momentum,

$$\partial_\mu T^{\mu\nu} = 0. \quad (2)$$

We use an equation-of-state which is compatible with lattice gauge results of ref. [26]. The above equations [27] are solved in full 3D space (τ, x, y, η_s) where τ , η_s , x , and y are the proper time, space-time rapidity, the two transverse coordinates, to obtain energy density e , pressure P , and local four fluid velocity u^μ , respectively. With $\tau_0 = 0.35\text{fm}/c$, the obtained plasma evolution successfully explained[2, 8] multiplicity distributions, rapidity distributions, p_t spectra and mean p_t dependence of multiplicity, Bose-Einstein correlations, and the ridge phenomenon of charged hadrons. Contrary to [2, 8], we employ here the initial condition for each given Pomeron number ν .

Now thermal photon emission can be treated in the same way as in heavy ion collisions [16], *i.e.*, the transverse momentum spectra of thermal photons at a given ν can be written as

$$\frac{dN}{dy d^2p_t}(\nu) = \int d^4x \Gamma(E^*, T) \quad (3)$$

with $\Gamma(E^*, T)$ being the Lorentz invariant thermal photons emission rate which covers the contributions from the QGP phase [29] and HG phase [30], $d^4x = \tau d\tau dx dy d\eta_s$ being the volume-element, and $E^* = p^\mu u_\mu$ the photon energy in the local rest frame. Here p^μ is the

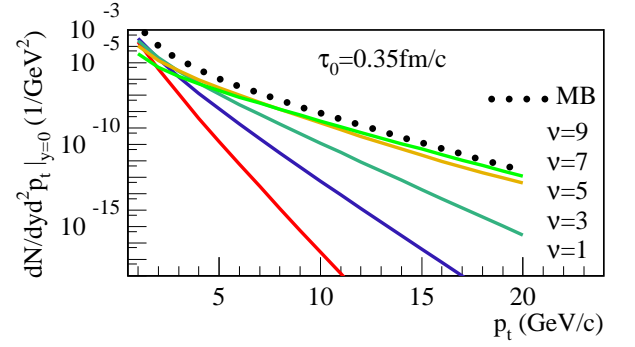


Figure 3: (Color Online) The thermal spectra given ν (solid lines) and the mini-bias case (dotted line). The different solid lines correspond to (from bottom to top) $\nu = 1, 3, 5, 7, 9$.

photon's four momentum in the laboratory frame, T and u^μ are the temperature and the local fluid velocity, respectively, obtained from solving eq.(2) for each Pomeron number ν . The Mini-bias thermal contribution reads

$$\frac{dN}{dy d^2p_t}(\text{MB}) = \sum_\mu \frac{dN}{dy d^2p_t}(\nu) * \text{Prob}(\nu).$$

In Fig.3 we plot the thermal spectra from given ν , including the factor $\text{Prob}(\nu)$ (solid lines) and the minimum-bias case (dotted line).

The corresponding thermal cross section $d\sigma^{\text{thermal}}/dy d^2p_t$ is then simply obtained by multiplying with the inelastic pp cross section (we use $\sigma_{pp} = 63.2$ mb). What is very interesting is the fact that the p_t region of 5-10 GeV/c is completely dominated by large values of ν . The smallness of $\text{Prob}(\nu)$ for ν around 7-9 is compensated by the very hard p_t spectrum, as compared to small ν values, due to the very high energy densities for large ν . This provides the very fortunate situation that “QPG effects” which are obviously more developed for large ν , are already visible in minimum bias spectra. From Figs. 2 and 3 it is also clear why we do not expect such a big effect at RHIC. Here large values of ν are strongly suppressed, having $\nu = 9$ for example is practically impossible, and therefore the large ν plasma effect cannot be seen.

Whereas the Pomeron number ν is the important quantity for theoretically defining event classes, we have to finally use real observables. Fortunately there is a strong relation between Pomeron number and the charged particle multiplicity. Fitting the values of the pseudorapidity density $dn/dy(y=0)$ for given ν , we get:

$$dn/dy(0) = 2.8147\nu + 4.3477.$$

In the upper panel of Fig. 4, the (pseudo)rapidity density $dn^\gamma/dy(0)$ of thermal photons versus $dn/dy(0)$ is plotted. Because photons are massless, the result is very sensitive to the lower limit in the transverse momentum integration[31], which is taken to be zero in our calculation. In the lower panel we plot the ratio $dn^\gamma/dy(0)$

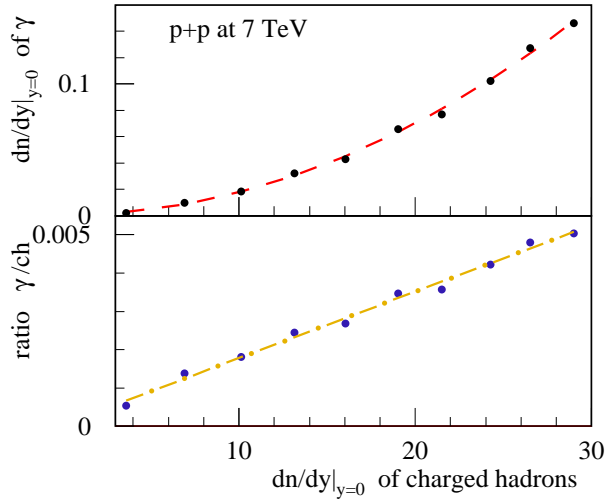


Figure 4: (Color Online) Upper panel: the rapidity plateau height of charged hadrons (squares) and thermal photons (dots) are plotted versus ν . The yellow bands on the left represent minimum-bias results. In the lower panel, we plot the ratio of the plateau heights of photons and charged particles (triangles). The dashed lines are used to guide the eye.

to $dn/dy(0)$. The lines in both panels are used to guide the eye. One can clearly see the linear dependence in the lower panel, which mean photon production increases quadratically with the charged particle multiplicity! This is understandable, because photon emission from a QGP is a volume process, integrated over time while hadrons are emitted from the freeze-out hypersurface, corresponding to a narrow window in proper-time. This strong increase of photon production with multiplicity is another reason why photons are a very good probe to investigate QGP production in high multiplicity pp events.

In summary, we illustrate that direct photon production at low and intermediate p_t is a good signal of QGP formation in pp scattering. The reason is that photon production is predicted to increase quadratically with the the charged particle multiplicity. Therefore high multiplicity events contribute considerably even to minimum bias photon production, and as a consequence at low and intermediate p_t values, the thermal production should be by far dominant compared to prompt photons.

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